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## Mycotoxin detoxication of animal feed by different adsorbents

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### Abstract

The contamination of animal feed with mycotoxins represents a worldwide problem for farmers. These toxins originate from molds whose growth on living and stored plants is almost unavoidable particularly under moist conditions. Mycotoxin-containing feed can cause serious diseases in farm animals resulting in suffering and even death and thus can cause substantial economic losses. The most applied method for protecting animals against mycotoxicosis is the utilization of adsorbents mixed with the feed which are supposed to bind the mycotoxins efficiently in the gastro-intestinal tract. Aluminosilicates are the preferred adsorbents, followed by activated charcoal and special polymers. The efficiency of mycotoxin binders, however, differs considerably depending mainly on the chemical structure of both the adsorbent and the toxin. This review describes the most important types of adsorbents and the respective mechanisms of adsorption. Data of the *in vitro* and *in vivo* efficacy of detoxication are given. © 2001 Elsevier Science Ireland Ltd. All rights reserved.

**Keywords:** Review; Mycotoxin detoxication; Activated charcoal; Aluminosilicate; Clay; Zeolite

### 1. Introduction

Mycotoxins are produced by several fungi, particularly by many species of *Aspergillus*, *Fusarium*, *Penicillium*, *Claviceps*, and *Alternaria*. They comprise a group of several hundreds of chemically different toxic compounds (William, 1989; Moss, 1996; Rotter et al., 1996; Sweeney and Dobson, 1998). The most common mycotoxins are aflatox-

ins, ochratoxin A, trichothecenes, zearalenone, and fumonisins.

Cereal plants may be contaminated by mycotoxins in two ways. First, there are fungi growing as pathogens on plants; secondly, there are fungi growing saprophytically on stored plants. In this context, it has to be considered that not all of these fungi form mycotoxins, i.e. the detection of fungi is not the same as the detection of mycotoxins because many fungi are not able to produce mycotoxins or produce them in different amounts depending on the substrate on which they are growing. However, high incidence rates of con-

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tamination of cereal grains and animal feed have been reported worldwide (Placinta et al., 1999; Spahr et al., 1999), so that the contamination of diets by mycotoxins and the carry-over of mycotoxin related compounds through the food chain (Ramos and Hernandez, 1996) have to be accurately controlled. Although in terms of acute toxicity even the most poisonous of the mycotoxins is far less toxic than the botulinum toxin (Moss, 1996), the consumption of mycotoxin contaminated diet may induce acute and long-term chronic effects resulting in a teratogenic, carcinogenic (mainly for liver and kidney), oestrogenic, or immunosuppressive impact not only on animals but also on man whereas animals usually suffer more due to grain of lower quality (D'Mello et al., 1999; Steyn and Stander, 1999; Casteel and Rottinghouse, 2000). In addition to the toxic effects, a mycotoxin contaminated diet may lead to other consequences like feed refusal, poor feed conversion, diminished body weight gain, increased disease incidence due to immune suppression, and interference with reproductive capacities (CAST, 1989; Lindemann et al., 1993; Kubena et al., 1998a) which are responsible for great economical losses.

In order to avoid mycotoxicosis, several strategies have been investigated (Doyle et al., 1982; Park, 1993; Bauer, 1994; Ramos and Hernandez, 1997) which can be divided into pre- and post-harvest technologies and into biological, chemical, and physical methods.

The best procedure to prevent the effect of mycotoxins is the minimizing of the mycotoxin production itself (Miedaner and Reinbrecht, 1999), e.g. by harvesting the grain at maturity and low moisture and storing it at cool and dry conditions which is difficult to perform in countries with a warm and humid climate. Furthermore, the growth of fungi and therefore the production of mycotoxins is limited by the use of propionic acid or ammonium isobutyrate. Feed additives like antioxidants, sulphur-containing amino acids, vitamins, and trace elements can be useful as detoxicants (Nahm, 1995).

Biological methods are not yet used in practice though the number of corresponding patents increases continuously (Erber, 1996; Duvick and

Rood, 2000). These methods include fermentation procedures with microorganisms. One example is the conversion of aflatoxin B<sub>1</sub> (particularly by *Flavobacterium auranticum*) to harmless degradation products. The conversions, however, are generally slow and incomplete (Sweeney and Dobson, 1998; Arici, 1999; Bata and Lásztity, 1999; Karlovsky, 1999).

Chemically, some mycotoxins can be destroyed with calcium hydroxide monoethylamine (Bauer, 1994), ozone (McKenzie et al., 1997; Lemke et al., 1999) or ammonia (Park, 1993). Particularly the ammoniation is an approved procedure for the detoxication of aflatoxin-contaminated feed in some U.S. states as well as in Senegal, France, and the UK. The average ammoniation costs vary between 5 and 20% of the value of the commodity (Coker, 1998). Main drawbacks of this kind of chemical detoxication are the ineffectiveness against other mycotoxins and the possible deterioration of the animals health by excessive residual ammonia in the feed.

The physical methods are focused on the removal of mycotoxins by different adsorbents added to mycotoxin-contaminated diets (Ramos et al., 1996a) with the hope of being effective in the gastro-intestinal tract more in a prophylactic rather than in a therapeutic manner. At present, however, the utilization of mycotoxin-binding adsorbents is the most applied way of protecting animals against the harmful effects of decontaminated feed.

## 2. Efficacy of different adsorbents for the binding of mycotoxins

Herein, the adsorbents are discussed particularly concerning efficacy, specificity, and the mechanism of the adsorption process. The latter is similar to a chemical reaction and therefore, the release of free energy ( $\Delta G$ ) is the driving force of every adsorption. The most important feature of the adsorption is the physical structure of the adsorbent, i.e. the total charge and charge distribution, the size of the pores and the accessible surface area. On the other hand, the properties of the adsorbate molecules, the mycotoxins, like po-

larity, solubility, size, shape and — in case of ionized compounds — charge distribution and dissociation constants play a significant role, too. Therefore, the efficacy of every adsorption process has to be investigated in regard to the particular properties of the adsorbate.

### 2.1. Activated charcoal

Activated charcoal which is formed by pyrolysis of organic materials is a very porous non-soluble powder with a high surface to mass ratio (500–3500 m<sup>2</sup>/g). Since the 19th century it has been used as an antidote against poisoning. Therefore, it might also inactivate mycotoxins. In aqueous solution, it can adsorb most of the mycotoxins efficiently (Table 1) whereas different activated charcoals have less or even no effects against mycotoxicosis (Table 2). This might be due to the fact that activated charcoal is a relatively unspecific adsorbent and, hence, essential nutrients are also adsorbed particularly if their concentrations in the feed are much higher compared to those of the mycotoxin. In other trials with goats, however, it was shown that high doses of activated charcoal are beneficial in an acute poisoning situation concerning the intake of high amounts of aflatoxins (Hatch et al., 1982).

### 2.2. Aluminosilicates (zeolites, HSCAS, clays)

Most studies related to the alleviation of mycotoxicosis by the use of adsorbents are focused on aluminosilicates, mainly zeolites and hydrated sodium calcium aluminosilicates (HSCAS), and aluminosilicate-containing clays, all consisting of aluminates, silicates and some interchangeable ions, mainly alkali metal and alkaline earth metal ions (Barrer, 1989; Mumpton, 1999). Clay minerals are primarily layered silicates with the common chemical formula  $[\text{Si}_2\text{O}_5]_{xy}^-$ , e.g. kaolin  $\text{Al}_4(\text{OH})_8\text{Si}_2\text{O}_5$ . Zeolites are composed of tetrahedrons of  $\text{SiO}_4$  and  $\text{AlO}_4$  as the two fundamental building blocks with the metal atom at the center of each tetrahedron. The common chemical formula is  $[\text{AlSi}_3\text{O}_8]_{xyz}$ , e.g. orthoklas  $\text{KAlSi}_3\text{O}_8$ , zeolite A  $\{\text{Na}_{12}[\text{Al}_{12}\text{Si}_{12}\text{O}_{48}] \cdot 27 \text{H}_2\text{O}\}_8$ . While the  $\text{SiO}_4$ -unit is electrically neutral, the  $\text{AlO}_4$ -unit car-

ries one negative charge which has to be compensated by positive charges, usually sodium ions as in zeolite A. Zeolites are similar to molecular sieves as well as to ion exchange resins and are suitable for the distinction of different molecules by size, shape, and charge. HSCAS contain calcium ions and protons which are exchanged against the naturally occurring sodium ions. They are a type of montmorillonite belonging to phyllosilicates which are composed of layers of aluminium and silicon connected in a 1:1 or 2:1 arrangement.

The applicability of aluminosilicates for the adsorption of mycotoxins (Table 1) has been studied for more than 20 years (clays: Masimango et al., 1978; zeolites: Mumpton and Fishman, 1977; HSCAS: Davidson et al., 1987; Ramos and Hernandez, 1997). Phillips et al. (1988) analyzed the in vitro binding capacities of different adsorbents which were representative for the major chemical classes of aluminas, silicas, and aluminosilicates and selected HSCAS as a possible suitable candidate for in vivo trials concerning the prevention of aflatoxicosis in chicken. HSCAS was shown to have a high affinity for aflatoxin B<sub>1</sub> forming a complex which was stable at temperatures of 25 and 37°C, in a pH range of 2–10, and in an elutropic series of solvents. When HSCAS was added in a concentration of 0.5% to chicken diets containing 7.5 mg/kg aflatoxin B<sub>1</sub>, the growth inhibitory effects were significantly decreased. In this study, the adsorption of HSCAS was thought to be chemisorption including the formation of strong bonds. Two years later, Phillips et al. (1990a) interpreted the binding mechanism as the formation of a complex by the β-carbonyl system of the aflatoxin with ‘uncoordinated edge site’ aluminium ions. Thus, HSCAS can be used as an ‘inorganic sponge’ sequestering aflatoxins in the gastro-intestinal tract of farm animals. Ramos et al., 1996b investigated the adsorption of aflatoxins to montmorillonite according to Freundlich and Langmuir isotherm calculations. They obtained a better fit of their adsorption data employing the Freundlich isotherm and suggested therefore the presence of a heterogeneous surface with different adsorption centers having different affinities for the adsorbate or the co-existence of

different adsorption mechanisms or both. The use of aluminosilicates for the adsorption of other mycotoxins was also tested, but with little success (Bauer, 1994; Ramos et al., 1996b; Lemke et al., 1998) except of a chemically modified montmorillonite with a binding capacity for zearalenone of 108 mg/g (Lemke et al., 1998). This clay was

derivatized with cetylpyridinium or hexadecyltrimethylammonium resulting in an increased hydrophobicity of the clay surface following a high affinity to the hydrophobic zearalenone. In contrast, a closely related organophilic phyllosilicate showed a significantly lower binding capacity (Schall et al., 2000). A surprisingly high binding

Table 1

In vitro adsorption of mycotoxins by different adsorbents

| Adsorbent                                                | Mycotoxin       | Adsorption capacity (mg/g) | Reference                      |
|----------------------------------------------------------|-----------------|----------------------------|--------------------------------|
| <i>Activated charcoal</i>                                |                 |                            |                                |
| Activated charcoal                                       | afl             | 10.0                       | Decker and Corby, 1980         |
| Activated charcoal                                       | afl/fum         | 120/11.0                   | Galvano et al., 1997           |
| Activated charcoal                                       | och             | 100.0                      | Bauer, 1994                    |
| Activated charcoal                                       | och/tri         | 124/9.9                    | Galvano et al., 1998           |
| <i>Aluminosilicates</i>                                  |                 |                            |                                |
| Aluminosilicates                                         | afl             | <0.02                      | Flores et al., 1999            |
| HSCAS (Milbond-TX®)                                      | afl             | 2.5                        | Ledoux et al., 1999            |
| HSCAS                                                    | afl             | 86.0                       | Phillips et al., 1988          |
| HSCAS                                                    | afl             | 62.4–72.4                  | Phillips et al., 1990b         |
| Montmorillonite                                          | afl             | 1.9                        | Ramos and Hernandez, 1996      |
| Aluminosilicates (Ethacal®, Novasil™, perlite, zeobrite) | afl             | 0.06–0.80 µg/g             | Scheideler, 1993               |
| Phyllosilicates, Bentonite                               | afl/och/zea     | 0.03–0.44                  | Schall et al., 2000            |
| Diatomaceous earth                                       | afl/och/zea/tri | 0.5–1.5                    | Natour and Yousef, 1998        |
| Montmorillonite <sup>a</sup>                             | zea             | 108                        | Lemke et al., 1998             |
| Montmorillonite                                          | zea             | 0.19                       | Ramos et al., 1996b            |
| Bentonite                                                | zea             | 0.11                       | Ramos et al., 1996b            |
| Sepiolite                                                | zea             | 0.07                       | Ramos et al., 1996b            |
| Mg trisilicate                                           | zea             | 0.02                       | Ramos et al., 1996b            |
| Bentonite                                                | och             | 1.5–9.0                    | Bauer, 1994                    |
| HSCAS                                                    | och             | 0–2.2                      | Bauer, 1994                    |
| Acidic clay                                              | cpa             | 0.74                       | Dwyer et al., 1997             |
| Neutral clay                                             | cpa             | 0.28                       | Dwyer et al., 1997             |
| Clinoptilolite                                           | cpa             | 0.08                       | Dwyer et al., 1997             |
| Montmorillonite                                          | erg             | 290                        | Huebner et al., 1999           |
| <i>Miscellaneous</i>                                     |                 |                            |                                |
| Yeast <sup>b</sup>                                       | och             | 1.2–8.6                    | Grünkemeier, 1990; Bauer, 1994 |
| Yeast cell walls (Mycosorb™)                             | zea             | 2.7                        | Völkl and Karlovsky, 1998      |
| Modified yeast cell walls extract                        | afl/och/zea/tri | 0.2–1.9                    | Howes and Newman, 2000         |
| Cholestyramine                                           | och             | 9.6                        | Bauer, 1994                    |
| Cholestyramine                                           | zea             | >0.3                       | Ramos et al., 1996b            |
| Crospovidone                                             | zea             | 0.3                        | Ramos et al., 1996b            |
| Cross-linked polyvinylpyrrolidone                        | zea             | 0.5–2.1                    | Alegakis et al., 1999          |

afl, aflatoxin; och, ochratoxin A; zea, zearalenone; tri, trichothecenes; fum, fumonsins; cpa, cyclopiazonic acid; erg, ergotamine.

<sup>a</sup> Derivatized with long-chain quarternary ammonium residues.

<sup>b</sup> 40% sterilized yeast, 60% fermentation residua of beer production.

Table 2  
In vivo adsorption of mycotoxins by different adsorbents

| Adsorbent                                                | Concentration (%) | Mycotoxin | Effects observed                                                                                                                                                                     | Reference                 |
|----------------------------------------------------------|-------------------|-----------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------|
| <i>Activated charcoal</i>                                |                   |           |                                                                                                                                                                                      |                           |
| Activated charcoal                                       | 0.5               | afl       | Decreased excretion of afl M <sub>1</sub> , no protective effects against aflatoxicosis                                                                                              | Edrington et al., 1996    |
| Super-activated charcoal                                 | 0.5               | afl       | Significant increase in body weight gains                                                                                                                                            | Edrington et al., 1997    |
| Activated charcoal                                       | High              | afl       | 100% survival of goats given a lethal dose                                                                                                                                           | Hatch et al., 1982        |
| Activated charcoal                                       | 0.5               | afl       | No effect                                                                                                                                                                            | Kubena et al., 1988       |
| Super-activated charcoal                                 | 0.5               | tri       | No effect                                                                                                                                                                            | Edrington et al., 1997    |
| Activated charcoal                                       | 10.0              | och       | Significant reduction of the och concentration in blood, bile, tissues of pigs                                                                                                       | Bauer, 1994               |
| <i>Aluminosilicates</i>                                  |                   |           |                                                                                                                                                                                      |                           |
| HSCAS, Bentonite                                         | 0.5               | afl       | Growth inhibitory effects on pregnant rats significantly diminished; ability of reproduction warranted                                                                               | Abdel-Wahhab et al., 1999 |
| Bentonite                                                | 0.5/1.0           | afl       | Growth inhibitory effects of broiler chickens diminished by 64 and 84%                                                                                                               | Araba and Wyatt, 1991     |
| Ethacal®                                                 | 0.5/1.0           | afl       | No significant effect (broiler chickens); ethacal® alone reduced feed intake and body weight and increased water consumption                                                         | Araba and Wyatt, 1991     |
| HSCAS                                                    | 0.5/1.0           | afl       | Growth inhibitory effects on broiler chickens diminished by 38 and 84%                                                                                                               | Araba and Wyatt, 1991     |
| HSCAS                                                    | 0.1/0.5           | afl       | Reduction of bioavailability of aflatoxins in the liver and blood of chickens in a dose-dependent manner                                                                             | Davidson et al., 1987     |
| HSCAS                                                    | 0.0–1.0           | afl       | Growth inhibitory effects on chickens diminished by 50–100%; feed conversions improved in a dose-dependent fashion; no full protection against liver or spleen weight changes by afl | Doerr, 1989               |
| HSCAS                                                    | 0.5               | afl       | Significant decrease of urinary excretion of afl M <sub>1</sub> in turkey poults when HSCAS simultaneously dosed with afl                                                            | Edrington et al., 1996    |
| HSCAS                                                    | 0.5               | afl       | Growth inhibitory effects on chickens diminished by 55–100%                                                                                                                          | Kubena et al., 1988       |
| HSCAS                                                    | 0.5               | afl       | 68% decrease in mortality of growing male turkey poults                                                                                                                              | Kubena et al., 1991       |
| HSCAS                                                    | 0.5               | afl       | Growth inhibitory effects on chickens diminished by 39–68% (2.5 mg afl/kg feed) and by 46–88% (5 mg afl/kg feed)                                                                     | Kubena et al., 1993b      |
| HSCAS (Milbond-TX®)                                      | 1.0               | afl       | Growth inhibitory effects on broiler chicks completely prevented                                                                                                                     | Ledoux et al., 1999       |
| Bentonite                                                | 0.5               | afl       | Growth inhibitory effects on pigs diminished by 87–89%                                                                                                                               | Lindemann et al., 1993    |
| HSCAS                                                    | 0.5               | afl       | Growth inhibitory effects on pigs diminished by 80%                                                                                                                                  | Lindemann et al., 1993    |
| HSCAS                                                    | 0.5               | afl       | Decrease of growth inhibitory effects, protective effects on gross hepatic changes                                                                                                   | Phillips et al., 1988     |
| Aluminosilicates (Ethacal®, NovaSil™, perlite, zeobrite) | 1.0               | afl       | Growth inhibitory effects on chickens diminished by 85–100%                                                                                                                          | Scheideler, 1993          |
| HSCAS                                                    | 0.5               | afl       | Growth inhibitory effects on average daily gain of pigs diminished by 82%                                                                                                            | Schell et al., 1993a      |

Table 2 (Continued)

| Adsorbent            | Concentration (%) | Mycotoxin | Effects observed                                                                                                                                      | Reference                 |
|----------------------|-------------------|-----------|-------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------|
| Clay                 | 1.0               | afl       | 3-Phase study: nursery, growing, metabolism phase; performance and liver function were enhanced, but not all functions restored                       | Schell et al., 1993a      |
| Calcium bentonite    | 0.25–2.0          | afl       | Growth inhibitory effects on average daily gain of pigs diminished by 64–82%                                                                          | Schell et al., 1993b      |
| Clinoptilolite       | 5.0               | afl       | Decreased food consumption of quail chicks diminished by 57%, growth inhibitory effects diminished by 70%                                             | Parlat et al., 1999       |
| HSCAS                | 0.5               | afl/och   | Growth inhibitory effects on chickens diminished by 65%, no effect against toxicity of och, little effect against toxicity of combined toxins         | Huff et al., 1992         |
| Inorganic            | 0.5               | afl/tri   | Growth inhibitory effects on broiler chickens diminished by 25%; no protective effect against T-2                                                     | Bailey et al., 1998       |
| HSCAS                | 0.5               | afl/tri   | Growth inhibitory effects on turkey poults diminished by 55–100% only for afl, no effect against T-2 induced toxicity                                 | Kubena et al., 1990       |
| HSCAS                | 0.5               | afl/tri   | Growth inhibitory effects on chickens diminished by 85% (afl), 76% (afl + tri), 3% (tri)                                                              | Kubena et al., 1993a      |
| HSCAS                | 0.25/0.375/0.8    | afl/tri   | Growth inhibitory effects on young broiler chickens diminished by 43%; no significant effect against tri toxicosis                                    | Kubena et al., 1998b      |
| HSCAS                | 1.0               | och       | No significant effect (pigs)                                                                                                                          | Bauer, 1994               |
| Bentonite            | 1.0/10.0          | och       | No significant effect (pigs)                                                                                                                          | Bauer, 1994               |
| HSCAS                | 0.5               | zea       | Reproductive effect of zea alleviated; protection against increase in gestation length, decrease in litter size and increase in kit mortality of mink | Bursian et al., 1992      |
| HSCAS                | 0.5/1.0           | tri       | No significant effect (pigs)                                                                                                                          | Patterson and Young, 1993 |
| Acidic clay          | 1.0               | cpa       | No significant effect (broilers)                                                                                                                      | Dwyer et al., 1997        |
| Neutral clay         | 1.0               | cpa       | No significant effect (broilers)                                                                                                                      | Dwyer et al., 1997        |
| Clinoptilolite       | 1.0               | cpa       | No significant effect (broilers)                                                                                                                      | Dwyer et al., 1997        |
| <i>Miscellaneous</i> |                   |           |                                                                                                                                                       |                           |
| Yeast <sup>a</sup>   | 5.0               | och       | No reduction of the och concentration in blood, bile, tissues of pigs                                                                                 | Bauer, 1994               |
| Cholestyramine       | 1.0               | och       | No reduction of the och concentration in blood, bile, tissues of pigs                                                                                 | Bauer, 1994               |

afl, aflatoxin; och, ochratoxin A; zea, zearalenone; tri, trichothecenes; fum, fumonsins; cpa, cyclopiazonic acid. The efficacy of each adsorbent was estimated by the effects on, for instance, the animal performance, clinical chemistry parameters, or body weight gain. As far as possible, it was calculated as percentage of the decrease of growth inhibitory effects.

<sup>a</sup> 40% sterilized yeast, 60% fermentation residua of beer production.

capacity of 290 mg/g for the alkaloid ergotamine was achieved with calcium montmorillonite (Huebner et al., 1999).

Related to *in vivo* trials, the amount of an adsorbed mycotoxin is difficult to calculate. Therefore, the efficacy of adsorption has to be determined by the animal performance, e.g. body weight gain, feed intake, mortality, concentrations of the corresponding mycotoxin in blood, tissues, and organs. The results from such feeding trials are presented in Table 2.

Regarding the applicability of aluminosilicates for the binding of mycotoxins, it can be concluded that they are very effective in preventing aflatoxicosis, but their efficacy against zearalenone, ochratoxin, and trichothecenes is limited. In addition to the narrow binding range concerning different mycotoxins, aluminosilicates have the disadvantage of showing high inclusion rates for vitamins and minerals.

### 2.3. Miscellaneous adsorbents

#### 2.3.1. Polymers

Cholestyramine is an anion exchange resin which is used for the binding of bile acids in the gastro-intestinal tract and for the reduction of low density lipoproteins and cholesterol. The *in vitro* binding capacity of this resin for ochratoxin A and zearalenone was 9.6 mg/g (Bauer, 1994) and more than 0.3 mg/g (Ramos et al., 1996b), respectively, but *in vivo*, cholestyramine had only a very small effect on the reduction of the ochratoxin concentration in blood, bile, and tissues.

Another adsorbent is crospovidone (polyvinylpyrrolidone), a highly polar amphoteric polymer the *in vitro* adsorbance of which was measured as 0.3 mg/g for zearalenone by Ramos et al. (1996b). Up to now, this polymer has not been tested *in vivo*. An improved cryogel of cross-linked polyvinylpyrrolidone recently showed increased values up to 2.1 mg/g (Alegakis et al. 1999).

#### 2.3.2. Yeast and products from yeast

Besides its excellent nutritional value, yeast or yeast cell walls can also be used as adsorbents for mycotoxins (Grünkemeier, 1990; Bauer, 1994). The *in vitro* adsorption of ochratoxin by yeast

(consisting of 40% sterilized yeast and 60% fermentation residua of yeasts used for beer production) is dependent on the pH being at maximum in acidic solutions (at pH 3: 8.6 mg/g, at pH 8: 1.2 mg/g). However, in trials with pigs employing a feed supplement of 5% of yeast, only a slight reduction of the ochratoxin A concentration in blood plasma, bile, and tissues was achieved. By the use only of yeast cell walls instead of whole cells, the adsorption of mycotoxins can be enhanced. The cell walls harboring polysaccharides (glucan, mannan), proteins, and lipids exhibit numerous different and easy accessible adsorption centers including different adsorption mechanisms, e.g. hydrogen bonding, ionic, or hydrophobic interaction. Therefore, it was possible to bind 2.7 mg zearalenone per gram of cell walls. The binding was rapid and reached equilibrium after only 10 min, which is superior to commercial available clay-based toxin binders (Völkl and Karlovsky, 1998, 1999).

In another context, it was shown that yeast killer toxins were adsorbed by the polysaccharides and not by the proteins or fatty acids of yeast cell walls (Radler and Schmitt, 1987) and that this adsorption was not unspecific because cellulose and glycogen were not able to bind killer toxins.

### 3. Conclusion

The applicability of different binders for the adsorption of mycotoxins was first investigated by *in vitro* experiments demonstrating that most of the mycotoxins were sufficiently bound by at least one adsorbent (Phillips et al., 1988, 1990b; Bauer, 1994; Galvano et al., 1997, 1998; Huebner et al., 1999), which was possibly derivatized, e.g. employing cetylpyridinium or hexadecyltrimethylammonium (Lemke et al., 1998). Adsorbents exhibiting high binding capacities *in vitro* were further tested in livestock and it was shown that some adsorbents are suitable to alleviate the toxic effects of specific mycotoxins. The addition of HSCAS for example resulted in almost total protection against aflatoxicosis (Kubena et al., 1988; Doerr, 1989; Ramos and Hernandez, 1996), but

its efficacy against zearalenone and ochratoxin was very limited (Bursian et al., 1992; Huff et al., 1992; Bauer, 1994) and against trichothecenes practically zero (Kubena et al., 1990, 1993a; Patterson and Young, 1993; Kubena et al., 1998b). So far, no single adsorbent was tested to be effective against most types of mycotoxins. However, the addition of different adsorbents or of very promising derivatized adsorbents to animal feed provides versatile tools of preventing mycotoxicosis.

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